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Overview of Results from the Fermilab Fixed Target and Collider Experiments

Hugh E. Montgomery

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

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Overview of Results from the Fermilab Fixed Target and Collider Experiments

Hugh E. Montgomery

Fermi National Accelerator Laboratory [1]
P. O. Box 500,
Batavia IL60510

Abstract.
In this paper we present a review of recent QCD related results from Fermilab fixed target and collider experiments. Topics covered range from structure functions through W/Z production, heavy quark production and jet angular distributions. We also include the current state of knowledge about leptoquark pair production in hadronic collisions.

INTRODUCTION

It could be argued that the volume of data which could, in principle, be described by QCD is already overwhelming. However, much of the available data are in regions in which the calculational difficulties of QCD are also difficult to overcome. It is therefore incumbent on experiment to lead us to a deeper understanding by probing new kinematic ranges and new processes where the theorists feel they should be able to confront the data.

In experiments at the Tevatron which satisfy these criteria, the processes studied range from relatively low energy production of single photons and charm through the production of the heavy vector bosons and the top quark at the highest energies currently available at accelerators.

The number of experiments is large, the results numerous. There are between twenty and thirty related parallel session papers at this conference. In this talk it is possible only to hint at the potential and the interest of the data available. We will include the exisiting preliminary results of searches for 1st generation (electron type) leptoquarks.

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[1] Fermi National Accelerator Laboratory is operated by the Universities Research Association for the U.S. Department of Energy.

As a concession to space and time we have decided *ab initio* to refrain from attempting to describe the beautiful work on multijets, their correlations, color coherence and the current attempts [1] to push into regions and processes sensitive to the BFKL approaches.

STRUCTURE FUNCTIONS

We commence our discussions of the data with the classic deep inelastic neutrino scattering. There are recent reanalyses [2,3] of the data from the CCFR experiment. The value for the QCD scale obtained by a complete fit of both F_2 and xF_3 yields $\Lambda_{\overline{MS}}^{(4),NLO} = 337 \pm 28(stat. + syst) \pm 13(HigherTwist)$ MeV. This is the highest value obtained from an analysis of a fixed target deep inelastic data set for some time. When expressed as a measurement of the strong coupling constant and plotted in comparison to other data in Fig. 1 we see that, contrary to previous analyses, very good consistency is obtained with the LEP measurements.

Also shown in Fig. 1 is the CCFR measurement [3] of α_S from their analysis of the Gross-Llewellyn Smith Sum Rule. This measurement hews more closely to the traditional values obtained by previous deep inelastic measurements.

An ambition of both experimentalists and theoreticians for many years has been to take high energy hadron interaction data and to feed them directly into the determinations of the parton distribution functions. This is now

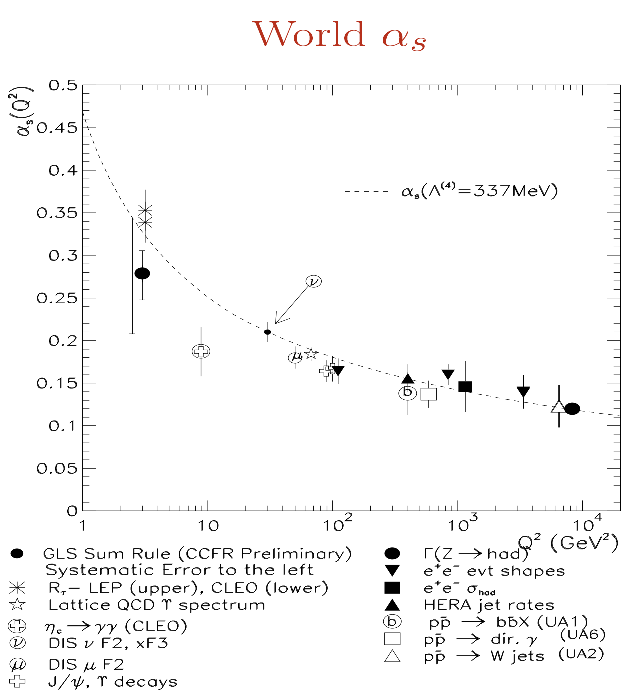

FIGURE 1. α_S Measurements from a variety of experiments including those from CCFR discussed in the text and in other talks at this conference.

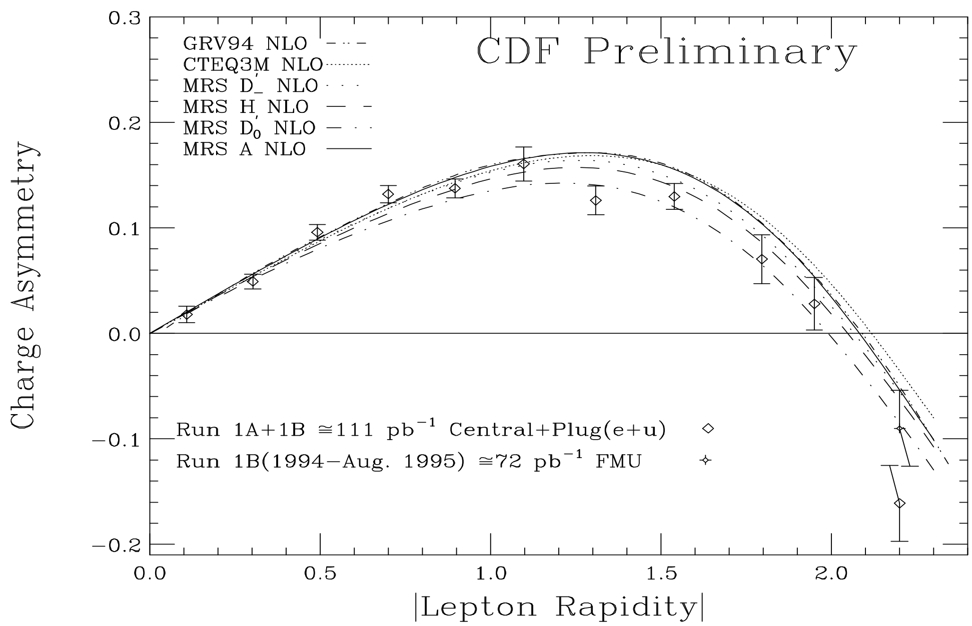

FIGURE 2. *W* Boson Asymmetry as a funtion of the lepton rapidity as measured by the CDF experiment.

happening with the W asymmetry data from CDF [4] shown in Fig. 2. Some of the compared calculations use parton distributions which fit the earlier lower statistics data from the same experiment. These new data extend the rapidity range and are considerably more powerful statistically.

The W data are at fixed mass and hence fixed Q^2. Variable Q^2 is offered by the more general Drell-Yan cross section measurements, see Fig. 3, also from CDF [4]. These show excellent agreement with the predictions and permit the determination of a limit on possible parton compositeness at a scale of about 2 TeV.

At much lower energies the E866 collaboration presented [5] some Drell-Yan data using a proton beam on both hydrogen and deuterium targets. These data are sensitive to the relative strengths of the $\bar{u}$ and $\bar{d}$ sea quark distributions at low x_{Bj}.

"ELECTROWEAK" QCD

The use of electroweak probes of the strong interaction is a well established technique especially when the bosons are space-like. With the advent of high luminosity collider data we can examine other aspects of boson production.

In Fig. 4 we show the inclusive associated jet multiplicity distribution for W and Z bosons from the CDF experiment. The simple logarithmic dependence is attributed to the increasing powers of α_S with increasing numbers of final state partons. The band is the prediction from a leading order pre-

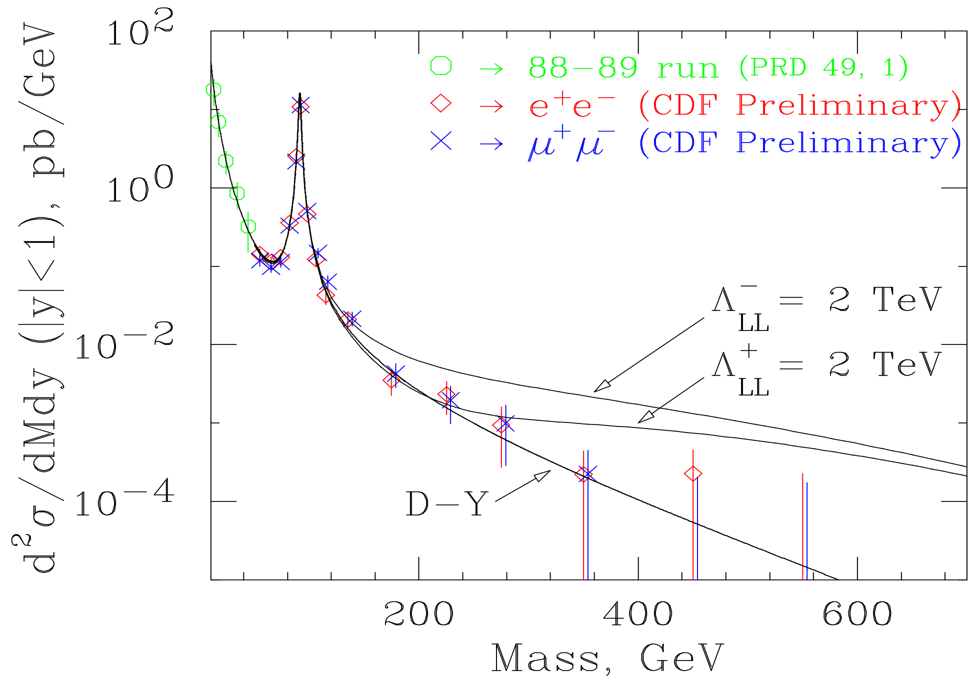

FIGURE 3. Drell-Yan charged lepton pair production as measured by the CDF experiment.

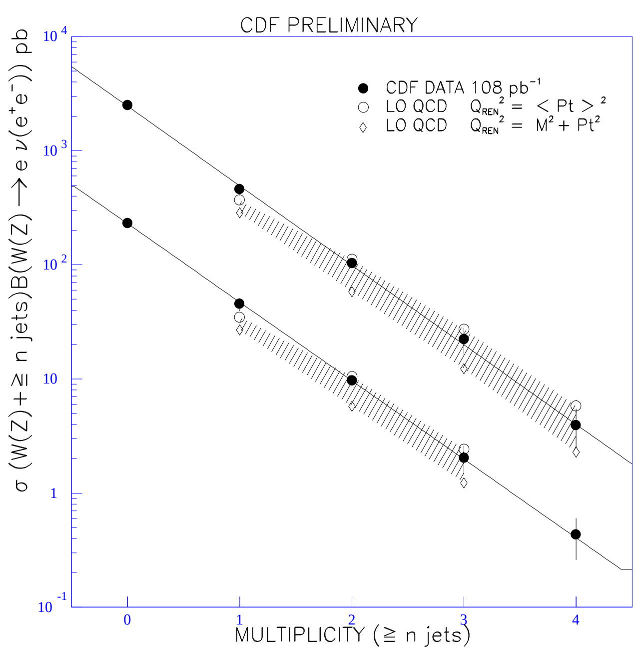

FIGURE 4. Jet multiplicity spectra for W and Z production

diction [6]. The common prejudice that there should be a strong similarity between the spectra for W and for Z is also borne out by the data. It is also true that at very low p_T the recoil spectrum of the Z and W bosons is well described by next-to-leading order calculations plus a resummation ansatz. Good agreement is seen as a by-product of the W mass analyses [7,8].

There are next to leading order calculations available for the production of a single jet in addition to the W. The most basic thinking suggests that the ratio of single jet to zero jet production should be fairly directly related to α_S. DØ has presented [9] data which display this ratio as a function of the minimum transverse energy of the jet; see Fig.5. In contrast to the measurements at the $Sp\bar{p}S$ [10] at a higher x_{Bj}, it is not possible to adjust the value of α_S in order to generate agreement between the theory and the data. Given the success of the phenomenology elsewhere, this is a major surprise and is currently not understood.

In general, the production of the light vector boson, the photon, is well described by theory. We see good agreement at high p_T in the collider data and an angular distribution similar to that of the W but different from that of jets, reflecting the different t-channel exchanges [13]. However at low p_T at colliders, there have been hints of deficiencies in the pure perturbative QCD description of the data. In the E706 data [11] shown in Fig. 6 on single photon and π^0 production with 530 GeV beam energy, the issue becomes more than a minor irritant. The data cannot be described by the current theory, even if the renormalization scale is permitted to reduce way below that which is natural; this also holds for π^0 production. The agreement is improved with

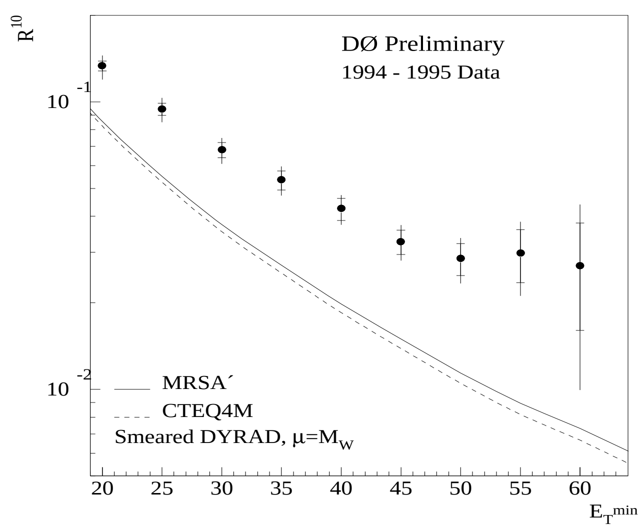

FIGURE 5. The ratio between the production of W-plus-one jet and W-plus-zero jets as a function of minimum jet transverse energy from the DØ experiment.

the introduction of a substantial ammount of k_T, an initial state transverse momentum for the partons. The average value of k_T is determined from the kinematics of π^0 pairs, see insert in Fig. 6.

The collider experiments attempt to measure the "k_T" directly in diphoton production. The vector sum of the photon E_T values is expected to provide a measure of the initial state "k_T". Data [12] from DØ on the net transverse momentum of the two photons are shown in Fig. 7. There are resummation ansätze [14] which exist, analogous to those for the low p_T W recoil, and they describe the data rather well.

HEAVY QUARK PRODUCTION CROSS SECTIONS

When we consider heavy quark production, we must now include all of top, bottom and charm. The top pair production cross section is displayed in Fig. 8. The measurements from CDF [15] and DØ [16] are in relatively good agreement with each other and are not in disagreement with any of the

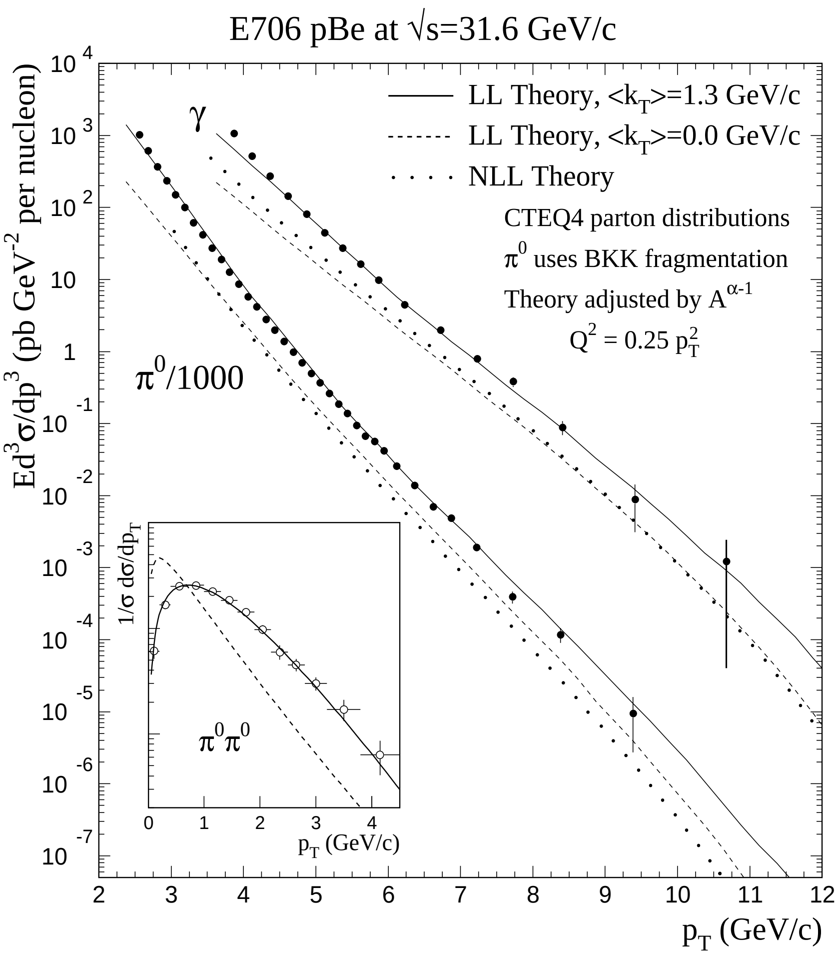

FIGURE 6. Single photon and neutral pion transverse energy spectra from E706.

relatively sophisticated calculations available [17].

The calculation of the bottom quark production cross section has also been considered tractable by QCD afficionados. The measurements [18] are consistently a factor two higher than the present calculations and a factor of four higher in the forward direction. For central production the optimistic view is that they are within the theoretical uncertainties associated with the calculation. With the inclusion of the forward, high η data, it seems that adjustment

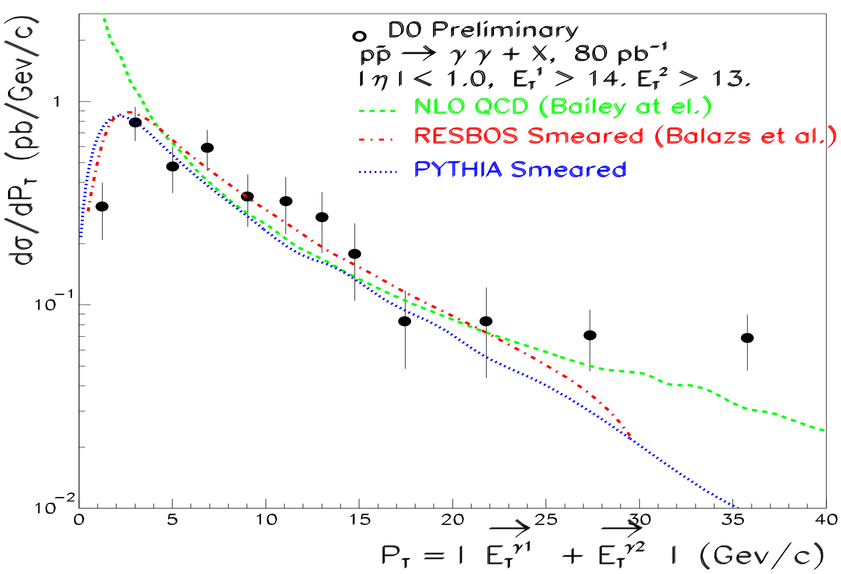

FIGURE 7. Spectrum of net photon E_T from the DØ Collaboration.

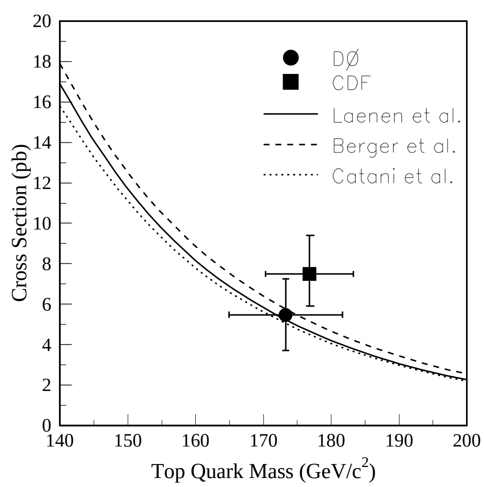

FIGURE 8. Top pair production cross section at the Tevatron Collider.

of the gluon distribution in an attempt to better describe these measurements should not be deferred for much longer.

There was some sense that these high energy data gave a picture which is slightly inconsistent with that offered by the lower energy measurements of UA1. Recent measurements [18] at 630 GeV from CDF and DØ at the Tevatron suggest that both the ratios shown in figure 9 and the absolute values from all three experiments are in good agreement when treated consistently. Further the ratio calculated by theory is in very good agreement with the data.

For charm production, there have been extensive reviews [19] of the attempts to describe these data. There is a major uncertainty associated with the charm mass. Some recent Tevatron fixed target measurements of the Feynman x distribution of charm production are shown in Fig. 10. Agreement of the calculations with the shape and also of the differences between pion production and proton production can be understood in terms of the relative stiffness of the gluon distributions in the two cases.

It would seem that the phenomenologists [19] are prepared to demonstrate that all the available data are consistent within the expected uncertainties associated with parameters such as the charm mass. A consistent fit of all data has not yet been attempted. Such a step might afford important insight on the relative gluon contributions in different processes and the possibility of

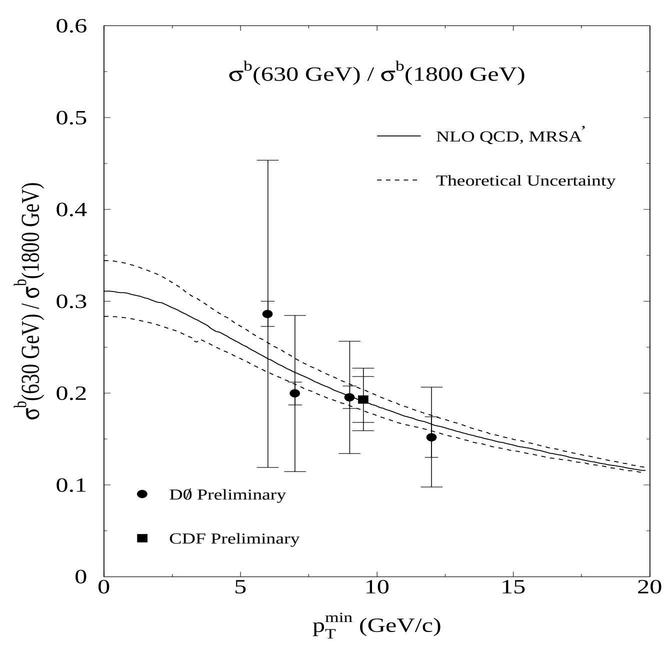

FIGURE 9. Ratio of bottom quark central production cross sections at 630 GeV and 1800 GeV.

checking against parton distribution determinations.

INCLUSIVE JETS

Dijet angular distributions are relatively insensitive to several systematic errors and also to the parton distribution functions. However they are rather sensitive to the structure of the theory. Figure 11 shows the recent data from DØ which demonstrate [21,22] a clear distinction between the leading order and next-to-leading order calculations. Data from CDF [23] have been used to set a lower limit on the parton compositeness scale of about 1.8 TeV. The DØ data give a lower limit of about 2 TeV. These limits are sensitive to choices of scale and ansatz at the level of about 0.1-0.2 TeV.

Inclusive jet production is the hallmark process of the high energy collider and the recent data sets access transverse momenta of 500 GeV. The data from CDF are shown in comparison to the theory in Fig. 12. The recent measurements from DØ with reduced systematic errors since 1996, are compared with theory in Fig. 13. The predictions are in remarkable agreement with the data whether from DØ or from CDF [24]. Discussions revolve around the existence or not of gradual divergences at the 30-40% level from the theory over a range of many orders of magnitude in cross section. Conclusions at this level are sensitive to a number of issues.

The experiments use different ranges of pseudo-rapidity reflecting the different sweet spots of their detectors. The energy calibration of the detectors for

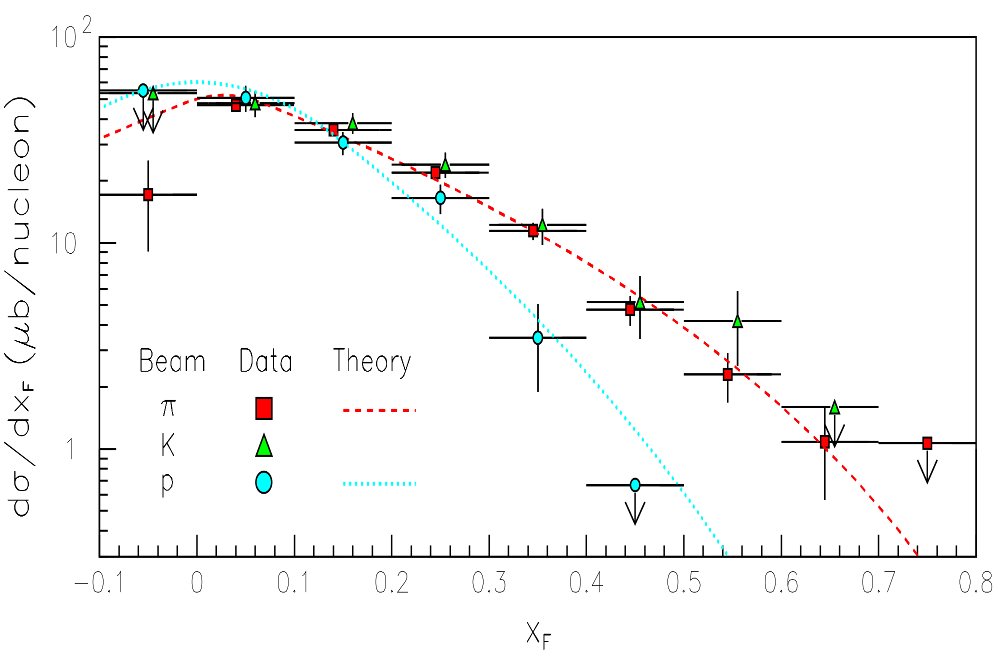

FIGURE 10. Charm X_F distributions for different beams from E769

jets is extremely difficult. By definition the highest E_T jets are not directly calibrated. Finally the most incisive statements can only be made with an

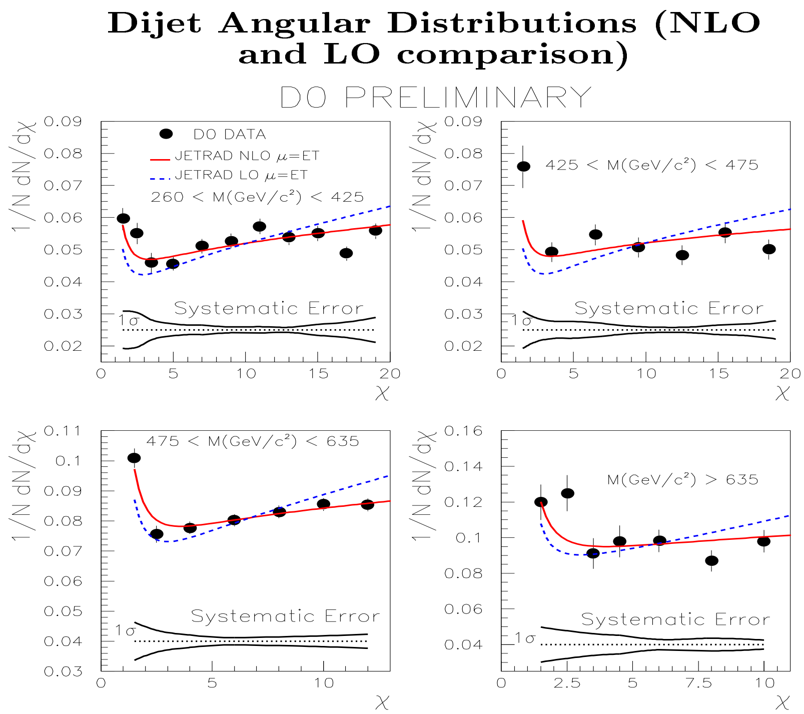

FIGURE 11. Jet Inclusives angular distribution from tyhe DØ Experiment

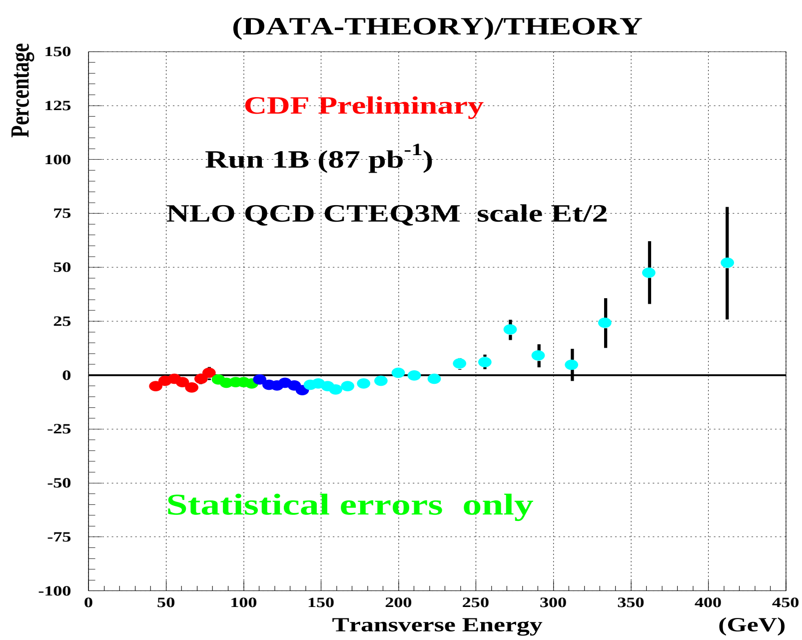

FIGURE 12. Ratio between experiment and theory for the inclusive jet E_T spectrum as measured by CDF in the central rapidity region.

understanding of all the error correlations in hand.

On the theory side, the results of any chosen calculation are dependent on the choice of parton distribution functions, the choice of renormalization/factorization scales, the separation between partons required for them to be declared separate, and also care must be taken with the provenance of the actual code. Some of these issues can substantially change the dependence of the results on transverse energy.

These issues are discussed [24] in detail at this conference so we will refrain from attempting a conclusion at this juncture.

LEPTOQUARKS

If leptoquarks exist they should be pair produced in hadron hadron collisions. The signature for a first generation leptoquark with 100% branching fraction(β) to electron plus quark, is two energetic electrons and two energetic quarks (jets) in the final state. In the case that this branching fraction is less than 100% then the complement leads to either electron plus neutrino (missing energy) plus two jets or, in the case when both leptoquarks decay to neutrinos, just two jets and missing transverse energy.

The DØ experiment has presented [25,26] preliminary results of searches in all of these channels. At the present time the analyses make little use of the

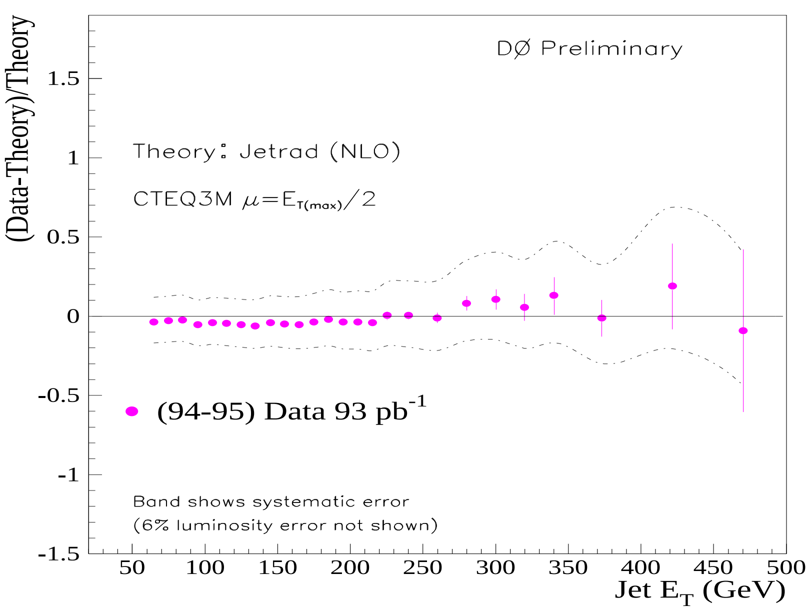

FIGURE 13. Ratio between experiment and theory for the inclusive jet E_T spectrum as measured by DØ in the central rapidity region.

specific decay characteristics of a leptoquark pair. The primary background is the production of Z bosonsand Drell-Yan production in conjunction with two jets. The resulting counts of signal candidates are three in each of the channels. This is consistent with background expectations of 2.9 ± 1.1, 4.0 ± 1.1 and 3.5 ± 1.2 events respectively.

DØ then calculates cross section limits for scalar quarks at 95% CL taking into account the variation of acceptances and efficiencies with mass. The cross sections for vector leptoquarks are substantially higher and, consequently so are the mass limits. Comparison with a calculation [27] of the cross section then leads to a mass limit as a function of branching fraction to electrons. These are shown in Fig. 14. With 100% branching fraction the limit is about 175 GeV. On the day of this talk, a new calculation [28], which attempts to take into account higher order effects, was submitted for publication. That calculation suggests that the cross sections are higher than in the previous calculation and would lead to the mass limit *rising* by about 15 GeV to approximately 190 GeV for a branching fraction of 100%.

DIFFRACTIVE PHYSICS

Diffractive physics is currently very popular. Diffractive processes are often depicted as involving t-channel exchanges of colorless pomerons. This leads

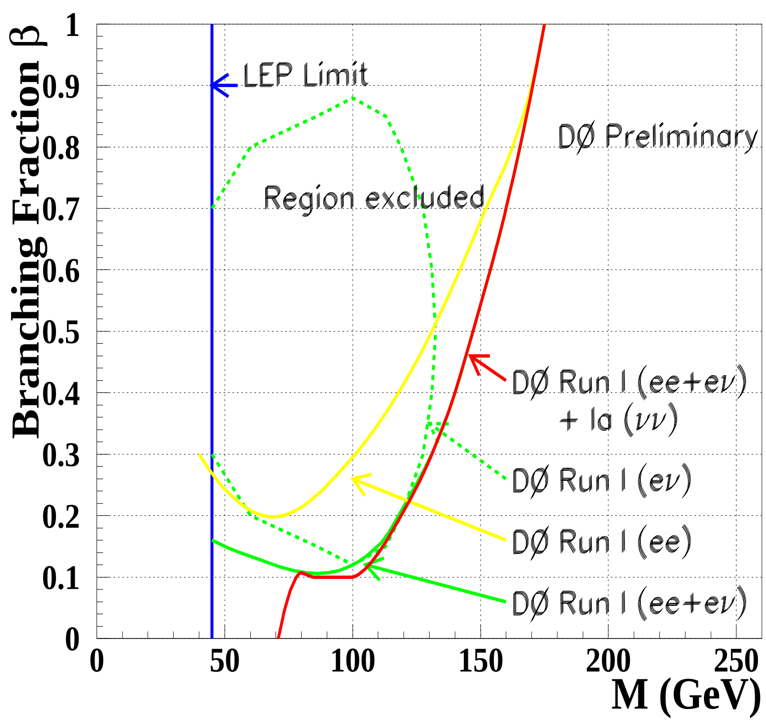

FIGURE 14. DØ 1st generation Leptoquark Limits as a function of β .

to the primary experimental signal, a range of rapidity which is essentially unpopulated. Requiring such *rapidity gaps* in various configurations has led to several quantitative results.

Both DØ [30] and CDF [31] observe these gaps between rather energetic jets, a central gap. There are theories which attempt to estimate the relative rates of such processes compared to the total cross section. Differing views of the nature of the pomeron can lead to different predictions. By comparing the rates for a given jet energy at both 1800 GeV and 630 GeV, DØ sees that, unexpectedly for some theorists, the signal is higher at the lower energy. Further at 1800 GeV when the energy of the jets is raised, the fraction with gaps also rises. In both cases, the "effective x_{Bj}" is higher.

Both experiments [32,33] see hard single diffractive di-jet production, an extension of the UA8 signal of several years ago. DØ has also seen the signal for double pomeron production characterized by two gaps between two central jets and the two beam regions. To achieve the sensitivity, they demanded a single gap in the trigger [30]. In addition CDF has recently submitted for publication an observation of diffractive W production [34] at the level of (1.15 $\pm$ 0.55)% of all W production which suggests that the pomeron is quarklike component(they estimate 70/diffractive di-jet measurements.

Finally I would like to finish with a small puzzle which comes from analysis of some muoproduction data from E665. These data are nicely complementary to HERA in energy and cover, in the main, a very similar Q^2 range. E665 has presented [35] their diffractive ρ production. The decay angular distributions demonstrate s-channel helicity conservation. They then show the change of characteristic of the ρ which is almost completely transversely polarised at Q^2 close to zero and rises to become strongly longitudinally polarized at $Q^2 = 10$ GeV^2. The Q^2 dependence of the production is consistent with that of the lower energy data and the higher energy HERA data. However the energy dependence does not smoothly extrapolate to the higher energy data; this is not understood.

CONCLUSIONS

It is straightforward to remark that the relevant data from the Tevatron experiments are abundant and discriminative. Some of the data are understood; some are incorporated, or will be, in the body of global analyses. Other data are less well understood. A concomitant conclusion is that those data deserve more attention. This applies to charm production, bottom production and vector boson production. In particular the latter already have substantial statistical power and in future data sets they will form the basis for mainstream QCD studies.

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